Owner Manuals Review and Taxonomy of ADAS Limitations in Partially Automated Vehicles

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ABSTRACT

In the context of highly automated driving, the driver has to be aware of driving risks and to take over control of the car in hazardous situations. The goal of this paper is to categorize and analyze the factors that lead to such critical scenarios. To this purpose, we analyzed limitations of Advanced Driver-Assistance Systems (ADAS) extracted from owner manuals of 12 partially automated cars available on the market. A taxonomy with 6 macro-categories and 26 micro-categories is proposed to classify and better understand the limitations of these vehicles. We also investigated if these limitations are conveyed to the driver through Human-Machine Interaction (HMI) in the car. Some suggestions are made to better communicate these limitations to the driver in order to raise his/her situation awareness.

CCS CONCEPTS

• **General and reference** → **Surveys and overviews**; • **Human-centered computing** → *Human computer interaction (HCI)*.

KEYWORDS

adas, level 2 car, limitations, owner manuals, partially automated vehicle, review

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1 INTRODUCTION

Context

More than 90% of car accidents are caused by human mistakes [6]. To mitigate this issue, as well as to allow the driver to safely engage into secondary activities (non driving tasks), car manufacturers are moving towards vehicles that integrate an increasing level of automation. Conditionally automated vehicles should be able not only to assist the driver but also to drive in particular conditions without human intervention. As a result, the roads are now populated by a rising number of vehicles equipped with Advanced Driver-Assistance Systems (ADAS). According to the Society of Automotive Engineers (SAE), six levels of automation can be distinguished,

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ranging from no automation (Level 0) to full automation (Level 5) [22].
In this paper, we only focus on Level 2 (L2) cars, the most advanced level of usable automation currently available. For vehicles belonging to this level, the driver performs the dynamic driving task, assisted by ADAS for both steering and acceleration/deceleration. Moreover, these vehicles require the driver to monitor completely the environment.

Motivation

Despite a clear trend toward safer roads (-57.4% of road fatalities between 1996 and 2016) [7], there are still lots of accidents on the roads (over 25,000 people killed in the European Union in 2016). Nevertheless, the technology used by automated cars is fallible, as shown by two recent accidents involving L2 vehicles and causing the death of one person. In March 2018, a Tesla Model X collided with a highway barrier, causing the death of the driver. Two months before, a Tesla Model S collided with a fire-truck stalled on the lane, fortunately with no severe consequences for the people involved. In the first case, the driver was blamed for the accident because he was not monitoring the environment as requested by the vehicle [25]. In the second case, the driver could not forecast the danger caused by a limitation of the Tesla Autopilot system, which is not able to detect a steady obstacle when a car in front of the vehicle is changing lane, a limitation reported in the owner's manual, p.77 [21]. Although these accidents received a lot of attention from the media, Tesla strongly defended their Autopilot system stating that "if you are driving a Tesla equipped with Autopilot hardware, you are 3.7 times less likely to be involved in a fatal accident" [38]. Even if Tesla supported their statements with statistics it turned out that the analysis performed by NHTSA had some flaws and needed correction [8]. Many accidents might be still avoided by increasing the drivers' awareness concerning limitations of partial automation and by designing better interfaces to increase driver's Situation Awareness (SA) and responsiveness to take-over requests (TOR). Understanding when and why driving systems may fail is not only crucial for avoiding accidents, but also for increasing the trust of car users and customers in partially and conditionally automated vehicles [34].

Contribution

The limitations of ADAS of L2 vehicles are analyzed in this paper. Our approach differs from previous reviews [26, 32, 37] because it is grounded on information provided by owner manuals from a large set of car manufacturers, instead that on the analysis of research literature. In particular, our analysis allows to highlight and identify driving scenarios that are critical for vehicles, providing a taxonomy for classifying the limitations of commercialized vehicles (Level 2). From the analysis of owner manuals, we also investigate if the current limitations of ADAS are conveyed to the driver through HMI in the car. We believe this work can help manufacturers and researchers to raise awareness of ADAS limitations, developing driver-adapted HMI for L2 cars and for future cars with a higher level of automation (L3 or more, cf. SAE classification). Such interactions would help to increase safety and to enrich the user experience for conditional automation.

2 RELATED WORK

In this section, we present an overview of related work for assessing the limitations of ADAS. Besides related work found in scientific literature, we focus this section on scientific surveys done on ADAS and protocols used to test them.

Surveys

Because of the large variety of ADAS available in the market and of the continuous improvement of such technologies, it is important to define different categories of ADAS. Lindgren et al. [26] propose a clustering of ADAS with eight categories in order to gather features that serve the same function. Longitudinal and lateral controls are examples of proposed categories and their distinction is crucial since it is also used in the SAE driving automation classification [22]. For each category, a definition of each system is provided to explain the abbreviations used in this context. The authors also provide a reflection on human factors issues using ADAS, focusing on driver's behavior, trust and acceptance or SA. The importance of factors such as trust and acceptance of ADAS have also been discussed by Biassoni et al. [12], who showed the crucial role of information about use limitation of the technology and level of automation for increasing the user acceptability. While increasing trust in the system is crucial for adoption (as well as for marketing purposes), Hoffman et al. [24] showed that overrated trust in the system can lead to a decrease in driver attention and an increase in risk of accident. In particular, the authors highlighted the importance of building a correct level of trust in the system, acknowledging its limitations. Stellet et al. reviewed testing methodologies and provided a reference framework for testing ADAS regarding three axes: test criteria and metrics, and test scenarios [37]. However, we could not find in scientific literature a comprehensive review of ADAS limitations. In this article, we try to overcome this lack through a review of owner manuals recommendations.

Test protocols and certifications

Since there are not many scientific papers dealing with limitations of ADAS, we focused on looking how these systems are tested and validated before being implemented in commercialized cars. Both EuroNCAP (European New Car Assessment Program) and NHTSA (National Highway Traffic

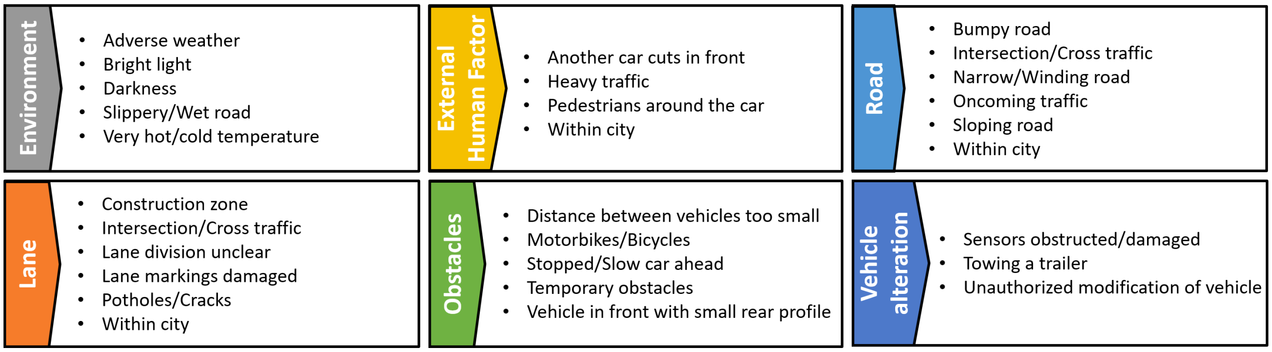

Figure 1: Classification of ADAS limitations into the macro-categories of the taxonomy

Safety Administration) evaluate the performance and reliability of ADAS. EuroNCAP uses a rating system with stars to provide safety details to the driver [2] about Adult Occupant, Child Occupant, Pedestrian Protection and Safety Assist which includes the test of ADAS. Both entities have set up several scenarios to test and rate these systems. According to the documentation provided on the respective websites [3–5], ADAS are tested with respect to the road test surface (dry, uniform, solid-paved, no irregularities), the slope of the road, the lane markings (color, width, reflectivity...) and the ambient conditions (temperature, humidity, wind speed or visibility). The particular conditions in which these test protocols are conducted show that all these parameters might be important factors for the proper functioning of ADAS. If these parameters are not optimal, we assume that the performance of ADAS may be seriously affected.

Empirical studies

Recently, several empirical studies have investigated how the presentation of ADAS to the final users can impact their trust, acceptance and awareness of the system. Beggiato et al. [11] showed that trust and acceptance increased steadily providing a correct description of the Adaptive Cruise Control. Moreover, Blomacher et al. [13] indicate that an incorrect preliminary description of the system leads to a poor situation awareness. Thus, it is important to provide a correct description of driving automation systems. This could be done both through the owner manual or an interactive tutorial as proven by Forster et al. [18].

3 METHODOLOGY

Database Creation

The aim of this study is to highlight the limitations of ADAS in L2 cars and their notification in current HMI. To reach this objective, a pool of partially automated cars representative of the current state of the market was selected. The criteria of the screening process applied to retain the final group of cars are:

1. The car must be a level 2 vehicle, with respect to SAE definition of level of automation [22], i.e., the car has at least the following two ADAS: longitudinal control of the car (generally advertised as Adaptive Cruise Control), and lateral control of the car (generally advertised as Lane Keeping System).

2. The owner manual needs to be publicly available, at least a fairly recent version.

A final pool of 12 vehicles has been retained (Table 1).

Table 1: List of chosen car models on the market (L2)

Manufacturer	Model	Year	Ref	Pages
Audi	A8	2018	[10]	350
BMW	7 Series	2016	[14]	312
Cadillac	C T6	2018	[15]	447
Honda	Acura	2018	[19]	450
Hyundai	Genesis	2016	[20]	503
Kia	Stinger	2018	[23]	560
Maserati	Ghibli	2018	[28]	367
Mercedes	Class S	2018	[29]	557
Nissan	Leaf	2018	[30]	578
Tesla	Model S	2018	[21]	193
Toyota	Lexus	2018	[39]	608
Volvo	S90	2018	[40]	284

From owner’s manual statements to micro-categories

Two kinds of information were extracted from each owner manual: the limitations of ADAS according to their function (longitudinal or lateral assistance) and the notification of these limitations through the HMI of the car (indicated or not).

We first extracted statements from sections of owner manuals that deal with the description, the use and the restrictions of ADAS. Only statements that contain at least one limitation of an automation system were selected. During this process,

324 statements collected from about 214 pages of owner's manuals have been examined.
The 324 statements have been grouped by three persons into a set of 26 micro-categories of limitations. In the remainder of this article, we will refer to these micro-categories as the "ADAS limitations" or just "limitations". Then, the number of statements assigned to each limitation has been counted. This step was done in separate processes (without discussion) by two persons, with an interrater agreement (Cohen's kappa) of 0.71 (good agreement) [16]. Differences in classification were discussed until agreement. A second extraction was done for each ADAS limitation, to assess if the system conveys this limitation to the driver through the interfaces in the car. A process similar to the first extraction was applied to the owner manuals.

Taxonomy creation and limitations classification

The ADAS limitations were then grouped into macro-categories. Limitations that share similar factors were clustered together to form a new macro-category. For example, a limitation due to the presence of rain (adverse weather) was closer to a limitation due to brightness (environmental condition) than to a limitation due to a pedestrian on the road (human factor). Six clusters emerged from this process. Inconsistencies in classification have been discussed by three authors in order to refine the definition of the different categories and ensure that every limitation can be fitted into a macro-category. To validate this process, four external persons (not among the authors) also classified the limitations into the six macro-categories, given them definition and an explanatory figure. A metric for measuring nominal agreement among many raters was calculated according to [33]. For this second clustering process, the fixed-marginal kappa is 0.73 (good agreement).

4 RESULTS

Taxonomy

The outcome of the classification is a taxonomy composed of 6 macro-categories and 26 micro-categories (Fig. 1). Fig. 2 illustrates a scenario that involves the limitations of a L2 vehicle belonging to the 6 macro-categories. Follows the list of the macro-categories and their definitions:

Environment
Limitation caused by an environmental condition. It includes the weather conditions (rain, snow, fog, ice, crosswinds, etc.), brightness, direct sunlight or temperature (see Fig. 2 (4)).

External Human Factor
Limitation caused by the behavior of a human out of the driving car, or anything with a human-like/unpredictable behavior, such as animals. This includes the behavior of other road users among the road traffic. It also includes pedestrians or cyclists around the car (Fig. 2 (1)).

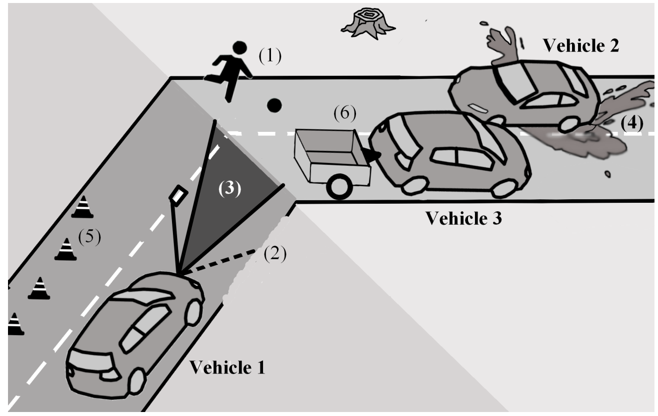

Figure 2: Examples of critical situations corresponding to macro-categories of the taxonomy with three L2 vehicles: External Human Factor (1), Lane (2), Road (3), Environment (4), Obstacles (5), Vehicle Alteration (6)

Road
Limitation caused by anything related to the road and considered as **non**-temporary. Examples include the shape and slope of the road such as narrow, winding or sloping roads (see Fig. 2 (3)).

Lane
Limitation caused by anything related to the road and considered as temporary. It includes all that is relevant to lane markings and road surface quality (potholes or cracks) (see Fig. 2 (2)). However, it excludes the limitations due to unmodifiable parameters of the road, such as its shape or its slope.

Obstacles
Refers to a limitation of the system due to static or mobile obstacles on the road, where the nature of the limitation is the shape of the obstacle, and not its behavior (see Fig. 2 (5)). It includes temporary obstacles on the lane or vehicles in front with a small rear profile. However, it does not include limitations due to the behavior of other road users.

Vehicle Alteration
Gathers limitations due to any alteration of the original state of the vehicle that worsens the performance of ADAS. It includes sensors obstructed or damaged, unauthorized modification of the vehicle, as well as modifications incompatible with driving assistance features, such as towing a trailer (see Fig. 2 (6)).

Two micro-categories did not fit into only one macro-category because they are related to several restricting factors. These two micro-categories were excluded from the calculation of the fixed-marginal kappa because the method developed by [33] allows only one answer per category. The

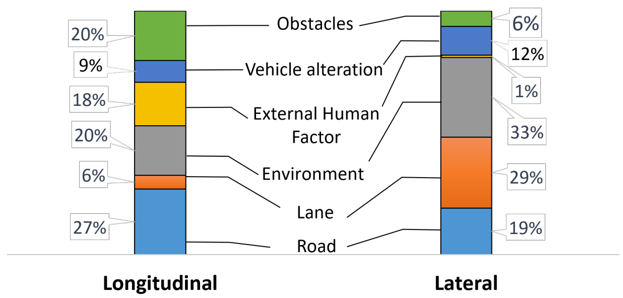

Figure 3: Distribution of ADAS limitations according to identified categories for longitudinal (left) and lateral (right) ADAS features

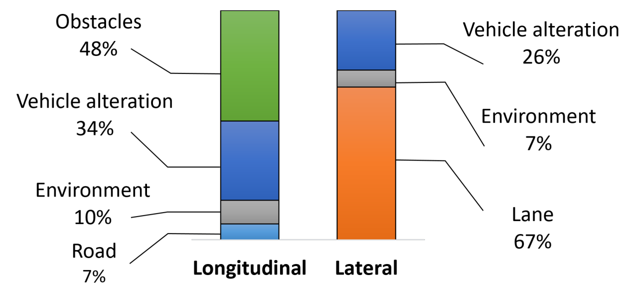

Figure 4: Distribution of limitations conveyed via HMI according to identified categories for longitudinal (left) and lateral (right) ADAS features

two cases were discussed by the authors as follow:
- Within city: driving in a city is problematic because it implies a lot of different parameters and issues, like pedestrian abundance, dangerous intersections, narrow streets or lane markings overlapping. Therefore, this limitation has been classified in Road, Lane and External Human Factor macro-categories.
- Intersection/Cross traffic: Intersections are complex situations to handle for ADAS features because of crossing lines and also because of roads coming from many directions. That is why this limitation has been classified in both Road and Lane categories.

ADAS Limitations in car manuals

Table 2 presents the results of our quantitative analysis for the limitations of current L2 cars on the market. The number of occurrences of each limitation in the 12 owner manuals is presented in the column *Man.* of Table 2, for both longitudinal and lateral ADAS.

Fig. 3 presents the distribution of ADAS limitations retrieved from owner manuals according to the six categories of the taxonomy. For the longitudinal assistance features (on the left), Road is the major factor of limitations using these features (27%), closely followed by Environment (20%), Obstacles (20%) and External Human Factor (18%). For example, limitations for these categories are, respectively, *"Narrow/Winding road"*, *"Adverse Weather"*, *"Stopped/Slow car ahead"* and *"Pedestrian around the car"*. These four micro-categories seem to be important factors of critical situations while using longitudinal ADAS. Vehicle Alteration (9%) and Lane (6%) do not appear to be major issues.

Environment (33%) and Lane (29%) appear to be relevant for the lateral assistance features. They are followed by Road (19%), Vehicle alteration (12%), Obstacles (6%) and External Human Factor (1%). For example, limitations for the four first categories are, respectively, *"Adverse Weather"*, *"Lane division unclear"*, *"Narrow/Winding road"* and *"Sensors obstructed/damaged"*.

ADAS Limitations through current HMI

Table 2 also presents the results of our analysis about the number of occurrences of limitations that are displayed to the driver via HMI. Based on the analysis of owner manuals, the column *HMI1* in Table 2 shows the number of cars displaying the limitation mentioned in its owner manual. The column *HMI2* shows the number of cars out of 12 displaying the limitation, even if it is not mentioned in the manual. Fig. 4 presents the distribution of the column *HMI2*, according to the categories of the taxonomy. For longitudinal ADAS, the most notified categories of limitations through in-car interfaces are Obstacles (48%) and Vehicle Alteration (35%). Environment (10%) and Road (7%) are notified less often than the two aforementioned categories. We can notice that there are no limitations belonging to External Human Factor and Lane categories that are notified to the driver while using longitudinal features.

For lateral ADAS, the limitations coming from the Lane category are the most notified to the driver (67%), followed by Vehicle Alteration (26%) and Environment (7%). We can notice that limitations from Obstacles, External Human Factor and Road categories are never notified to the driver through HMI when using lateral features.

Combination of results

Previous results show which are the main ADAS limitations and if they are displayed to the driver. We summarized this analysis by calculating an indicator that highlights the limitations that are often mentioned in the owner manuals but rarely communicated to the driver through HMI. For each one of the 26 limitations, we calculated the ratio of cars notifying it to the driver through HMI among those mentioning it in the manual. The computed score is calculated according

Table 2: Number of occurrences of limitations in owner manuals

Conditions	Longitudinal				Lateral			
	Man.	HMI1	HMI2	Ratio	Man.	HMI1	HMI2	Ratio
Adverse weather	10	0	0	0%	11	0	0	0%
Another car cuts in front	5	0	0	0%	-	-	-	-
Bright light	6	1	1	16.7%	9	0	0	0%
Bumpy road	2	0	0	0%	1	0	0	0%
Construction zone	2	0	0	0%	9	0	0	0%
Darkness	-	-	-	-	6	0	0	0%
Distance between vehicles too small	-	-	-	-	4	0	0	0%
Heavy traffic	4	0	0	0%	-	-	-	-
Intersection/Cross traffic	2	0	0	0%	2	0	0	0%
Lane division unclear	-	-	-	-	11	8	9	72.7%
Lane markings damaged	-	-	-	-	7	3	9	42.9%
Motorbikes/Bicycles	8	0	0	0%	-	-	-	-
Narrow/Winding road	11	1	1	9.1%	8	0	0	0%
Oncoming traffic	6	0	0	0%	-	-	-	-
Pedestrians around the car	10	0	0	0%	-	-	-	-
Potholes/Cracks	-	-	-	-	2	0	0	0%
Sensors obstructed/damaged	6	5	10	83.3%	7	3	7	42.9%
Slippery/Wet road	8	1	1	12.5%	7	0	0	0%
Sloping road	9	0	1	0%	7	0	0	0%
Stopped/Slow car ahead	9	1	1	11.1%	-	-	-	-
Temporary obstacles	4	1	1	25%	3	0	0	0%
Towing a trailer	2	0	0	0%	3	0	0	0%
Unauthorized modification of vehicle	3	0	0	0%	3	0	0	0%
Vehicle in front with small rear profile	4	0	0	0%	-	-	-	-
Very hot/cold temperature	1	1	1	100%	3	1	3	33.3%
Within city	3	0	0	0%	1	0	0	0%

to the formula:

$$Ratio = \begin{cases} \frac{N_{HMI1}}{N_{Man.}}.100, & if N_{Man.} \neq 0 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

with N_{HMI1} the number of cars displaying the limitation mentioned in its owner manual (HMI1 columns in Table 2) and $N_{Man.}$ is the number of occurrences of the limitation in the owner manuals (Man. columns in Table 2). The results of this score are shown in the columns Ratio of Table 2 for both longitudinal and lateral ADAS limitations.

If we focus first on longitudinal ADAS, we can see that 18 out of 21 limitations are conveyed to the driver by less than 25% of the cars of the pool that mention these limitations in their manuals. Even worse, 14 of the mentioned limitations are not displayed by any car of the pool. The only two limitations that are displayed to the drivers and have a high ratio are *Sensors obstructed/damaged* and *Very hot/cold temperature*.

The results from this score show the same trend concerning lateral ADAS. Indeed, we can see that 15 out of 19 limitations are not communicated by any car of the pool mentioning these limitations in their manuals. Only four limitations are conveyed to the driver when using lateral driving assistance features, which are *Lane division unclear*, *Lane markings damaged*, *Sensors obstructed/damaged* and *Very hot/cold temperature*. Besides problems related to sensors (obstructed or damaged), problems related to poor lane markings are often communicated to the driver. When lane markings are damaged and ADAS cannot be used, the driver receives the information through a logo on the dashboard (for 9 cars out of 12) or on the head-up display (1 car). However, other challenging factors for assistive systems that are often mentioned in the manuals such as *Adverse weather* (11 cars out of 12 but ratio of 0%) or *Bright light* (9 cars out of 12 but ratio of 0%) should really be conveyed to the driver.

5 DISCUSSION

Interpretation of results and stakes

One of the main outcomes of this study is the definition of a taxonomy that helps individuating and classifying the main factors that affect the proper functioning of ADAS in L2 cars. We believe that the contribution of such a taxonomy can be very high, both for the research and the industrial fields. Indeed, this study helps to depict the current status of ADAS that are available on the market and it individuates the critical factors that may lead to potential critical situations while driving a L2 car. As researchers and car manufacturers often use different terms to refer to ADAS limitations [9], the taxonomy could help to establish a common frame and common definitions for reporting ADAS limitations. This might help to report better information about ADAS limitations in user manuals, raising the awareness of the driver about the related risks, and in scientific papers, providing a common framework to report and discuss ADAS limitations. The good inter-rater agreement obtained shows that the taxonomy is clear and easy to apply. We also propose a summary of limitations of automation which are communicated to the driver by manuals and interfaces. The owner manuals analysis shows that some limitations of ADAS are common to many L2 cars of the pool. However, some of these limitations are conveyed to the driver only by few cars. Our analysis provides insights on which limitations of ADAS should be better conveyed through interfaces in the car in order to increase the SA of the driver. Both car manufacturers and academic researchers could use these results in order to develop in-car HMI concepts to fill this gap.

Propositions of concepts

Several concepts could be implemented in future cars in order to increase drivers' awareness about ADAS. For some limitations raised in this study such as *adverse weather*, *narrow, winding and sloping roads* or *construction zones*, one solution could be to provide contextual reminders to the driver through geo-localization services or crowd-sourced road data services (e.g., the Waze app [1]). This technology could also be used to measure SA, as suggested by [36].

Other concepts based on HMI that are currently not implemented in cars can also be explored. Some research has been already done in order to develop HMI concepts for increasing SA using different modalities such as augmented reality [35], ambient light display inside the vehicle [27], 3D sound cues, [41] physical avatars on the dashboard interacting with the driver [42] or multimodal anthropomorphic AI agents [31]. These concepts would alert the driver and lead her/his gaze to elements that are present in the immediate surrounding area of the car, such as pedestrians, temporary obstacles, or other vehicles in the traffic. Therefore, it would increase driver's awareness about these limitations of automation that have been raised in this study.

6 LIMITATIONS AND FURTHER WORK

Limitations of the study

Even though this paper provides a deep insight into what are the limitations of L2 cars, there are some limits to this study. The whole analysis is based on information retrieved from owner manuals that are provided by car manufacturers. Nevertheless, an owner manual is definitely a way for the car manufacturers to protect themselves against a complaint from the driver, especially if an accident occurs in one of the critical situations mentioned in the manual. Car manufacturers might mention in the manual also limitations that are unlikely to occur or that might affect the proper functioning of the ADAS only in specific cases, just to avoid liability in case of accident. Therefore the actual criticality of a limitation and its correlation with a concrete risk of accident cannot be stated accurately from owner's manual upon with reservations. Indeed, our analysis only assesses the frequency of apparition of each limitation in owner manuals. Each limitation that appears in an owner manual is counted once, but the severity of the limitation could not be quantified with such method. Nevertheless, as car manufacturers do not publicly report the cause of ADAS failure in case of accident, we believe that owner's manuals are still the most complete source of ADAS limitations of L2 cars so far. For L3 cars, instead, more quantitative data are available through disengagement reports [17].

Further work

We choose to lead our study on Level 2 cars because we used owner manuals as sources. Since Level 3 cars are commercialized but not legally usable, we could not use them for this analysis. Yet, it could be interesting to expand the research to Level 3 by using reports of accidents and disengagements during test protocols, in order to investigate if the critical factors raised in our analysis correlate with factors of accidents and disengagements of Level 3 cars.
At a more technical level, we are planning to implement the most critical limitations raised in this study in a simulated driving environment, such as adverse weather (rain), lane markings damaged, and also winding and sloping roads. An experiment will be lead on a driving simulator where these limitations appear in the external environment of the car and will be conveyed to the driver in order to increase her/his SA. We want to investigate what kind of interactions can increase driver's SA when factors of ADAS limitations appear in the external environment of the vehicle.

7 CONCLUSION

This paper proposed an analysis of limitations of ADAS in Level 2 cars. To get a better overview of these limitations, a taxonomy composed of 6 macro-categories (External Human Factor, Lane, Road, Environment, Obstacles, Vehicle Alteration) and 26 micro-categories has been created. This taxonomy has been used to classify the limitations of ADAS retrieved from owner manuals, with a good inter-rater agreement. Through the analysis of results, we evidenced the categories of factors that are the most frequently mentioned in L2 cars owner manuals, for both longitudinal and lateral ADAS. This taxonomy allows to easily highlight the limitations of current L2 vehicles that are on the market. In addition, an analysis has been made to investigate if these same limitations are communicated to the driver through HMI in the car. Results show that numerous limitations are often mentioned in manuals but almost never notified to the driver, causing a lack of SA for the driver. We hope that the limitations highlighted in this study can help car manufacturers and researchers to not only raise drivers' awareness about ADAS but also to help them developing new HMI concepts to make partially and conditionally automated driving safer.

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